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Procedia Engineering 25 (2011) 92 – 95

Procedia Engineering

www.elsevier.com/locate/procedia

Proc. Eurosensors XXV, September 4-7, 2011, Athens, Greece

A wireless module for vibratory motor control and inertial sensing in capsule endoscopy

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Abstract

The development of active locomotion schemes for endoscopic capsules - as opposed to passive traversal of the gastrointestinal tract by natural peristalsis - is expected to significantly enhance the diagnostic, and foreseeably, the therapeutic scope of these devices. The use of external magnetic fields is currently regarded as the most promising approach for the active guidance of endoscopic capsules. In addition to this, the potential of using vibrations to reduce the friction between the capsule and the gastrointestinal tissue is currently under investigation. Towards this end, a prototype has been developed, which integrates on-board a vibrating motor and a triaxial accelerometer, along with an electronics module, that allows remote control of the motor and wireless transmission of the inertial data to a host PC. *Ex-vivo* tests confirm both the efficacy of vibrations for reducing friction, and the sufficiency of the inertial sensing scheme in capturing the characteristics of the capsule's vibrations.

Keywords: Robotic capsular endoscopy; vibrating motor; active locomotion;

1. Introduction

Wireless capsule endoscope (WCE) guidance by external magnetic fields is currently regarded as the most promising approach for endowing endoscopic capsules with active locomotion capabilities [1][2]. However, friction between the capsule and the gastrointestinal (GI) tissue limits the maneuvering

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doi:10.1016/j.proeng.2011.12.023

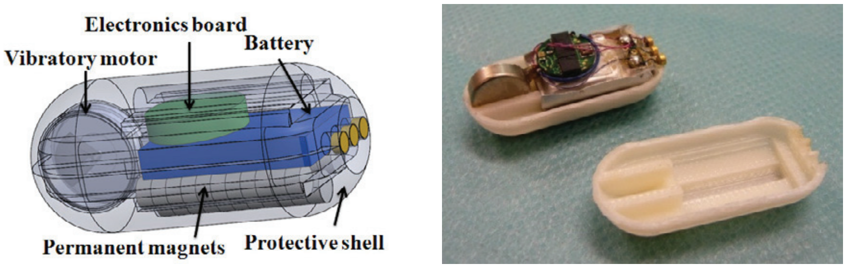
precision, potentially even leading to tissue damage; traction forces up to 8 times the capsule weight have been recorded when pulling the capsule through porcine intestinal tissues. In order to reduce this friction, the use of capsule vibrations has been proposed in [3] and is further evaluated here. Inductive powering may be used to meet the energetic demands of the on-board vibratory actuators [4].

We present a miniaturized capsule-shaped prototype, which integrates a coin-like vibrating motor, an on-board battery, a custom electronics module and a triaxial accelerometer, and provides wireless communication of the capsule with an external host. The prototype has been evaluated using a custom test-bench and a human-machine interface, aimed at studying the reduction of the traction forces needed to manipulate the capsule, as well as the accuracy of the inertial sensing of the vibrations.

2. The capsule prototype

2.1. Mechanical system design

A miniaturized capsule-shaped prototype (15mm diameter, 34mm length, 8,2g weight) was developed (Fig. 1). A core component of the capsule is the coin-like shaftless vibrating motor (model 310-101, Precision Microdrives Ltd, UK), which generates centripetal forces up to 0.8g, utilizing an eccentric mass rotated at frequencies up to 200Hz (controlled by the electronics board). The magnets and battery have been placed at the bottom side of the capsule, in order to lower the center of mass of the assembly, while keeping the vibrating motor in a vertical position to exploit maximum vibration effects. The triaxial accelerometer, placed at the prototype's center of mass, can be used to measure the capsule vibrations' amplitude and frequency. The protective shells were fabricated from ABS plastic using a 3D printer, and were glued together to render the capsule waterproof. Three magnetic contacts provide access to the battery (for charging and voltage measuring) and allow resetting and waking up of the microcontroller.



(a) (b)

Fig. 1. *(a) Computer-aided design model of the vibrating capsule, indicating its main components, and (b) assembled capsule prototype.*

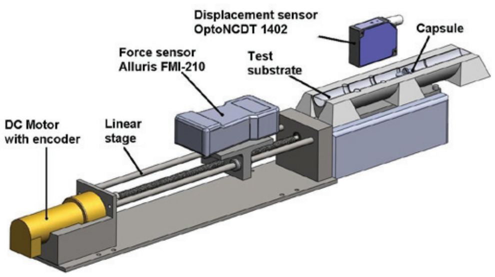
2.2. Electronic system design and software implementation

A custom wireless miniaturized control board was developed for PWM-based control of the motor's rotational velocity and for obtaining data from the integrated triaxial accelerometer sensor (LIS331DL, STMicroelectronics Inc., Switzerland). The electronics board exploits a system-on-chip component (CC2430, Texas Instruments, USA), which integrates a 8051 microproceessor core with ZigBee-compliant wireless functionality, and is small enough to allow deployment inside the capsular device. The overall electronics board prototype, including the IEEE 802.15.4 compliant transceiver is 9.6mm in diameter and has a total thickness of about 2.5mm [5].

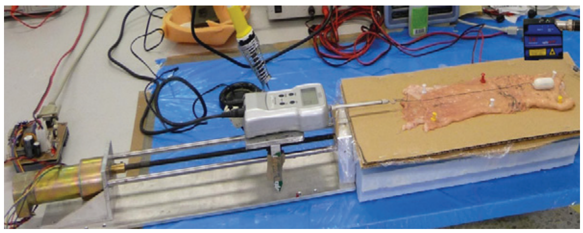
The specific application involves very strict timing requirements for interfacing with the acceleration sensor and controlling the vibrating motor, which necessitate the implementation of a real-time embedded software framework for the data acquisition and control processes. To this end, event-driven finite-state-machine code was developed, which achieves wireless bi-directional communication with an external host, allowing high data rates for both the inertial sensing and motor control tasks. This implementation takes place within a low-level pseudokernel system running in the embedded microcontroller, which allows an average response time of 20ms and a wireless communication rate of 52kb/s [5]. With regard to the accelerometer in particular, a robust state-driven task has been implemented, to optimize the acquisition time of the inertial information data, in order to fully exploit the sensor's 400Hz update rate. The implemented strategy relies on recording a set of acceleration data in a volatile buffer array with a defined time scheduling and then transmitting them at each communication cycle (frequency of 400Hz through the software data packet transmission strategy). A transmission rate of 50Hz has been achieved for the commands sent by the host to control the speed of the motor. Finally, a high-level human-machine interface, which was developed in LabVIEW 8.6 (National Instruments, USA), is used to wirelessly operate the capsule from a host PC.

3. Experimental methods and results

Extensive experiments were performed to validate the accelerometer output, as well as to measure the friction reduction of the integrated vibrating capsule over open porcine intestinal tissue. As shown in Fig. 2, the experimental setup consisted of a custom-made linear stage, a high accuracy force sensor (FMI220, Alluris GmbH, Germany: sampling frequency 1kHz, accuracy of 1mN) and a laser interferometer distance sensor (optoNCDT1402, microepsilon, Germany: sampling frequency 1.5kHz, accuracy 1μm). The prototype was placed over a total of 6 layers of open small intestine tissue, and was pulled, via a thin unelastic string attached to the force sensor, at a constant linear velocity of 6mm/s, for a total distance of 220mm. The vertical displacements of the vibrating capsule were measured by the displacement sensor. A custom graphical user interface was also developed, in order to adjust and control the linear stage, as well as to record data from the accelerometer, the force gauge and the displacement sensor.



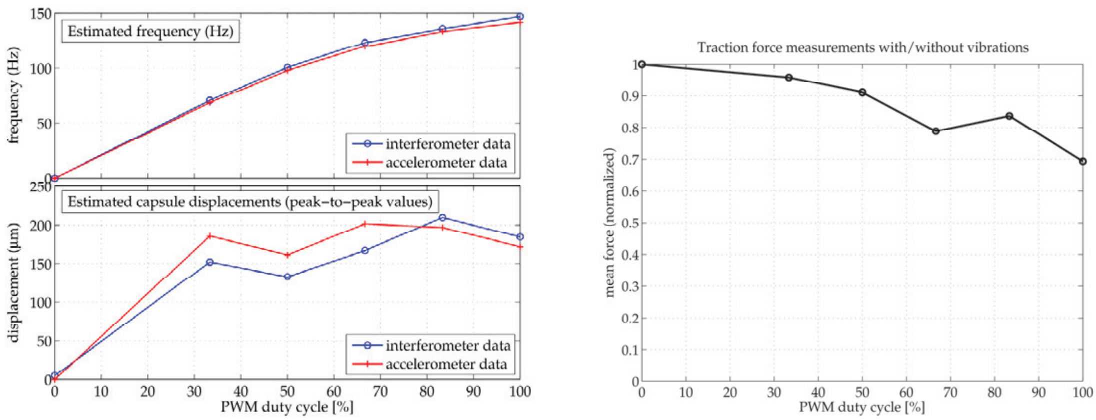
(a)



(b)

Fig. 2. A schematic diagram (a) and a photograph (b) of the employed measurement setup, showing the linear stage, the force and displacement sensors used and the initial capsule position.

A correlation between the accelerometer and displacement sensor measurements was observed up to 150Hz, verifying that the developed sensing system can provide reliable estimates for both the frequency and the amplitude of the capsule's vibrations (Fig. 3a). Moreover, our results confirmed the friction reduction using capsule vibrations (Fig. 3b), demonstrating a reduction of up to 30% of the mean traction force required to move the capsule prototype at a constant speed over porcine small intestine tissue layers.



(a) (b)

Fig. 3. (a) Comparison of the obtained measurements from the on-board accelerometer for the frequency and the amplitude of the capsule's vertical vibrations, against those obtained from the external displacement sensor. (b) Reduction of the traction force as the vibration frequency increases, for movement of the capsule over intestinal tissue at a linear velocity of 6 mm/sec.

4. Conclusion

Tests indicate correlation between the inertial (on-board accelerometer) and external (laser distance sensor) measurements (Fig. 3), confirming that the first can provide reliable estimates for the frequency and amplitude of the capsule's vibrations. In addition, reduction of traction forces up to 30% was achieved by the implementation of inertial vibrations at various frequencies. Future work will consider the use of the inertial sensor data for distinguishing between different areas of the GI tract, as well as for adjusting on-line the motor speed, in order to optimize the frictional reduction.

Acknowledgements

This work was supported in part by the European Community, through the FP6 IST R&D project VECTOR (contract number 0339970). The authors would like to acknowledge the contributions of the project partners in various aspects of the present work.

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